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THE DETERMINATION OF THE POSITION OF THE MOON BY PHOTOGRAPHY.

BY HENRY NORRIS RUSSELL.

The value of meetings of scientific societies in stimulating investigation is not confined to the reading and discussion of papers. Many other schemes, which never appeared on the printed programs, have had their inception on such occasions. For example, at the meeting of the American Philosophical Society, ten years ago, the present writer happened upon the late Professor E. C. Pickering and Professor E. W. Brown, deep in the discussion of some astronomical topic. Joining in the conversation, he found them considering the possibility of determining the Moon's place in the heavens by photography, as a supplement to and control upon meridian observations. Having had some experience in photographic measurements, he suggested a plan of attack. Professor Pickering's response was immediate and highly characteristic. "Will you write me a letter, stating in detail just how you think the photographs should be made? Then, if we make them according to these directions, will you have enough of them measured and reduced to see what are the possibilities of the method?" The offer was accepted on the spot, and thus began an observational campaign which is still in progress, and bids fair to continue for years to come.

The present summary is contributed as an illustration of the advantages of coöperation between institutions—in this case, the three oldest American Universities: Harvard, Yale and Princeton.

The primary obstacle to be overcome was the great difference in brightness between the Moon and the stars which have to be used as points of reference. To get stars enough (at least three within 2°30′ of the Moon) it is necessary to go below the eighth magnitude, and the exposure necessary to get good images is more than a thousand times as long for the stars as for the Moon.

This fundamental problem was solved by Professor Pickering, by the use of an occulting disk, a little larger than the clear aperture of the instrument, and set up several feet in front of it. The shadow of this disk protects the objective from the light of the Moon, while the light of stars which are not too near the Moon's limb can pass by it on one side or another and reach the plate. Good star images can thus be obtained without fogging the plate with diffused moonlight. To get an image of the Moon, the disk can be turned edgewise, allowing the light to pass for a fraction of a second. The times of beginning and ending of this short exposure are recorded automatically on a chronograph.

In this way excellently measurable images of both the stars and the Moon can be secured on the same plate; but another danger is incurred. If the driving clock is not of exemplary behavior, the telescope may be directed toward a slightly different point of the heavens during the short exposure on the Moon, and, on the average, during the long one on the stars. It is therefore necessary to employ an instrument which has a mounting of the highest mechanical excellence.

For this reason the 10-inch Metcalf Telescope of the Harvard College Observatory was used, with aperture reduced to 3.5 inches. The occulting screen was 5 inches in diameter, and carried by a pole nine feet long. With this equipment, the normal exposure of ten minutes gave measurable images of stars between the magnitudes 6 and 8.5. The exposures on the Moon varied from 0.2 to 0.6 seconds, according to the phase, and averaged $0^s.28$—less than 1/2000 of that on the stars. This gave lunar images which were sharp at the edge, but by no means opaque—a great advantage for measurement.

The photographic observations were all made by Professor E. S. King of Harvard, with notable success, very few plates indeed having to be rejected as deficient.

The measurement and reduction of these plates was carried out at the Princeton University Observatory. It can be recommended as an excellent training for students, for it involves the application of all the corrections previously known to astronomical photography, and of a few new ones, invented as the need for them appeared.

The measurement is simple enough. Three or four reference stars are chosen, which must have accurately known positions, and should lie within 2° from the Moon if possible, and form a triangle or quadrilateral enclosing it. It was usually possible to find three stars satisfying these conditions in the recent zodiacal catalogs (Lick, Edinburgh and Cape). If not, the A. G. catalogs were used, and a fourth star added. A réseau of 5^{mm} squares was impressed photographically on each plate before development, and formed a permanent system of reference, to which the rectangular coördinates of the star images could be referred. Eight or ten points on the Moon's limb were also measured on each plate—taking care to keep to the fully illuminated portion, which sometimes demanded a rough calculation if the Moon was nearly full.

In reducing the measures, the first step was to find the Moon's center. This was done by fitting a circle to the measured points on the limb by least-squares, and taking its center as that of the Moon. Before carrying out this process, the measures had to be corrected for the influence of refraction, which distorts the outline of a circular disk into an ellipse with its shortest axis vertical. This effect, which is so conspicuous for the setting sun, amounts at high altitudes to but a fraction of a second of arc, but ignoring it would have resulted in the introduction of systematic error.

The chief source of error in this process arises from the irregularities of the Moon's limb—mountains and valleys seen in profile—which are much larger than the errors of measurement of the photographs. Tho the accuracy of the determination of the center is considerably reduced by these irregularities, the photographic method has here a decided advantage, for the concluded center depends on many points of the limb, and conspicuous elevations or depressions can be avoided during measurement, or given reduced weight in the solutions, while in meridian observations certain definite points of the limb (preceding, following, north or south) have necessarily to be observed, and the influence of elevations or depressions at these points comes in to its full magnitude. For example, a certain region of depression, fully $2''$ below the normal level, showed up so often in our measures that we came to speak colloquially of "falling into the hole" whenever we came upon it anew. This region was directly visible on the photographs as a flattening of the limb, and was so situated that the point observed during transit observations would often fall in the deepest part of it, producing an error of $2''$ in the Moon's observed longitude.

The effects of these irregularities can be very largely eliminated by the application of the "limb corrections" determined by Dr. Hayn. Thirty-eight plates were reduced anew, applying these corrections. The resulting changes in the final positions of the Moon averaged only $\pm 0^s.015$ and $\pm 0''.17$ (without regard to sign) and were so small that it did not seem worth while to go to the labor of applying similar corrections to the remaining plates. The observational data have, however, been published in such a form that any one who chooses may work out these corrections for himself.

Another advantage of the photographic method, closely related to the last, is that the Moon's semidiameter can be determined from the plates themselves. It was found that this varied with the photographic density of the Moon's image and increased by about 1″.3 from the thinnest to the densest images (after allowing for the variations in the apparent semidiameter due to changes in the distance). By estimating the density of the images by comparison with a standard scale, and taking means, a table of corrections for photographic irradiation, depending on the density of the image, and applicable to the semidiameters interpolated from the American Ephemeris, and corrected for augmentation, was constructed. These corrections were negative except for the densest images, showing that the photographic irradiation was less than the assumed visual irradiation of 1″.5, which has been applied in computing the semidiameters in the Ephemeris. It was found that the introduction of these mean corrections gave considerably better results than the attempt to determine the Moon's radius separately from each plate.

In June, 1913, the objective of the Metcalf Telescope was refigured, shortening the focal length by about five per cent, and greatly improving the color correction. Tho this change produced no sensible effect on the appearance of the images, it altered the corrections for irradiation greatly, making them slightly smaller for the dense images than for the thinner ones. New values of the corrections were therefore determined, and the calculated positions of the Moon were corrected to correspond to these.

It is probable that the semidiameter observed visually is subject to corrections for irradiation which are as large as in the case of the photographs, and may be as variable; but no equally satisfactory method of correcting for such variations seems to be known.

Once the Moon's center has been found, the right ascension and declination are determined substantially as in the case of an asteroid. Standard coördinates of the stars are computed from their catalogued positions, and plate constants determined which enable the measured coördinates on the plate to be turned back into right ascension and declination. The resulting positions are mean places, and have to be brought up to apparent place in the usual way, and corrected rigorously for parallax, before they are compared with the Ephemeris. Most of the correction for refraction is made automatically in the determination of the plate-constants; but a small correction for second-order terms remains, which was fortunately easy to handle.

After the instrumental change in 1913, the plates which had previously been exposed flat, were curved to correspond with the focal surface of the objective, in the manner devised by Professor Pickering. This change compelled the application of still another correction to the calculated positions of the reference stars on the plate. The resulting alterations in the computed position of the Moon averaged 0″.4 in each coördinate.

The complete measurement and reduction of one plate forms a good day's work for a practiced computer.

The measures of the reference stars showed that the combined influence of the errors of the photographic positions and the star catalogs, and of unknown proper motions in the ten or twelve years interval between the epochs of the two, corresponded to a probable error of ±0″.57 in either coördinate. Known proper motions were of course applied. One of 0″.7 per year came up on one of the very first plates to be measured—and only one other as large on the next five hundred plates. After correction of the plate-constants for refraction, it appeared that the two sets of réseau lines were very nearly perpendicular—the angle between them differing from 90° by only 1″.9 ± 1″.2, but that the scale values along the two axes differed by 8 parts in 100,000. When the alterations were made in 1913, the plate holder was shifted so that the long axis of the plates ran east and west, instead of north and south. The effect just described thereupon changed sign, proving that it was due to an error of the réseau, and not to optical distortion of the field. The latter must be very small, not exceeding one part in sixty thousand.

The accuracy of the final results is best measured by the agreement of pairs of plates taken on the same night. From 450 plates the probable error of one determination of the Moon's R. A. comes out $\pm 0^s.049$ (corresponding to ±0″.68 at the mean declination) and that of an observed declination ±0″.68. The errors of measurement of the photographs contribute relatively little to this—the principal components arising from the irregularities of the Moon's limb, and the abnormalities of the driving clock, and of refraction, at the moment of exposure on the Moon. The smallness of the errors of the last named type was tested, at the very beginning of the campaign, by measuring plates of bright stars, exposed with the occulting screen in the same fashion as the Moon. The final positions of the Moon are nearly equal in precision to the best meridian observations, and have the great advantage that their systematic errors are likely to be entirely different.

The observational errors can not be determined by comparing observations made on different nights, because (as is well known) the errors of Hansen's lunar tables, on which the places given in the Ephemeris are still based, are now large, and vary by several seconds of arc during a month, owing to errors and incompleteness in the periodic terms in longitude. The errors in latitude are comparatively small. The resulting errors in right ascension are always positive, and ranged from $0^s.5$ to $1^s.3$ during the period covered by the observations. The errors in declination run up to 6″, and are positive when the Moon is coming north, but negative when it is going south.

Up to the present time 588 plates have been measured and reduced at Princeton. The results for 11 of these are printed in the *Harvard Annals*, Vol. 72, No. 1; for 204 more, in *H. A.* 76, No. 7; for 273 others, in *H. A.* 80, No. 11; while those for 100 more are in press, completing a continuous record of the errors of the lunar tables from the latter part of 1910 to the end of 1917. The preliminary work on the eleven plates was done by Dr. A. H. Joy and the writer; all the rest have been handled by Miss Fowler, Miss Borton and Miss Fuller, computers at the Observatory. Funds for the prosecution of the work were provided by the Elizabeth Thompson Science Fund, from the Lunar Tables Fund of Yale University, thru Professor Brown, and by a gift to the Princeton University Observatory by the late Mr. A. D. Russell, a Trustee of the University.

The resulting corrections to the Moon's tabular place were communicated to Professor Brown, who made use of them, along with the Greenwich meridian observations, in investigating the errors of the tables. The two series of observations confirm one another completely with regard to the character and amount of these errors. This agreement in view of the radical difference of the two methods of observation, indicates that both are very nearly free from systematic error—a highly satisfactory conclusion.

Work upon these plates at Princeton was interrupted early in 1918 by the diversion of the whole energy of the Observatory staff into war activities. The taking of plates at Harvard has been continued, and it is hoped to resume measurement in a short time.

In view of the irregular, and so far inexplicable, deviations of the Moon's observed motion from gravitational theory, it will probably be worth while to continue the observations for an indefinite period, both to keep track of the fluctuations of long period, and to determine whether these are accompanied by short period displacements not accounted for by theory.

Another possible application of the method, suggested by Professor Brown, is the making of simultaneous observations at stations in the northern and southern hemispheres. One naturally thinks that the object of such observations would be to determine the lunar parallax; but it turns out that the distance of the Moon can be calculated more accurately from its period (cleared of perturbations) and the force of gravity at the Earth's surface than it can be found by direct observation. Hence the observations can best be used to get the distance between the two terrestrial stations—that is, to find the ellipticity of the Earth.

A variant on this scheme would be to set up one of the observing stations on some oceanic island, such as Hawaii, and the other in the United States. The distance between the two places can of course be computed from their observed latitudes and longitudes, but for an isolated station the latter are affected by "station errors" due to local attraction of the plumb-line, which might be serious on an island rising out of deep water, and could not be determined, as in the case of land stations, by geodetic connection with other places. In such a case it might actually be worth while to impress the Moon into geodetic service as the third vertex of a triangle. By taking two or three hundred plates at each station, the angle at the Moon could be determined with a probable error of about $\pm 0''.05$. This would be equivalent to determining the geocentric angle between the stations with a probable error of $\pm 3''$. Station errors in mountainous countries are often much greater than this.

Princeton University Observatory,
March 1, 1920.